Transfer Learning for fast Gravitational Wave Event Characterization

Cristiano Sabiu
Natural Science Research Institute
University of Seoul

Elahe Khalouei
Hyung Mok Lee (이형목)
Center for the Gravitational-Wave Universe
Seoul National University

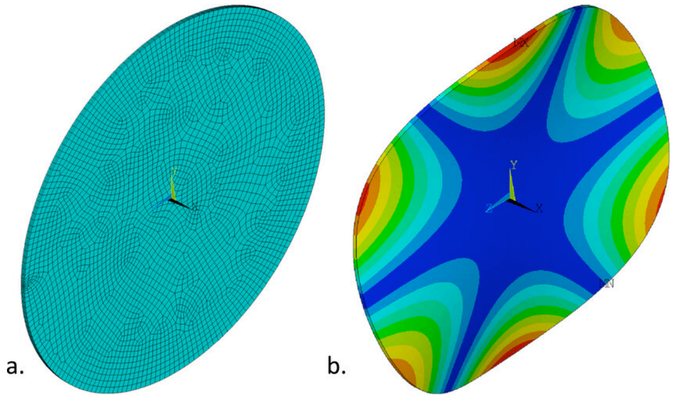
2024/10/28 11th KIAS Workshop on Cosmology and Structure Formation

Gravitational Waves

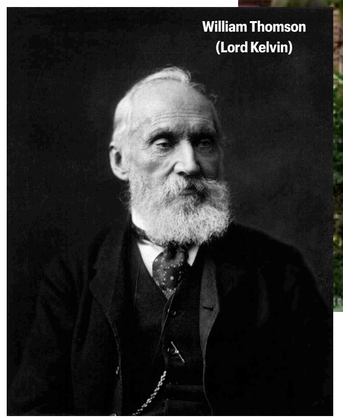


In 2006, in my final year undergraduate project (with Prof Shiela Rowan) I tested the vibrational modes of the proposed interferometer test masses

University of Glasgow







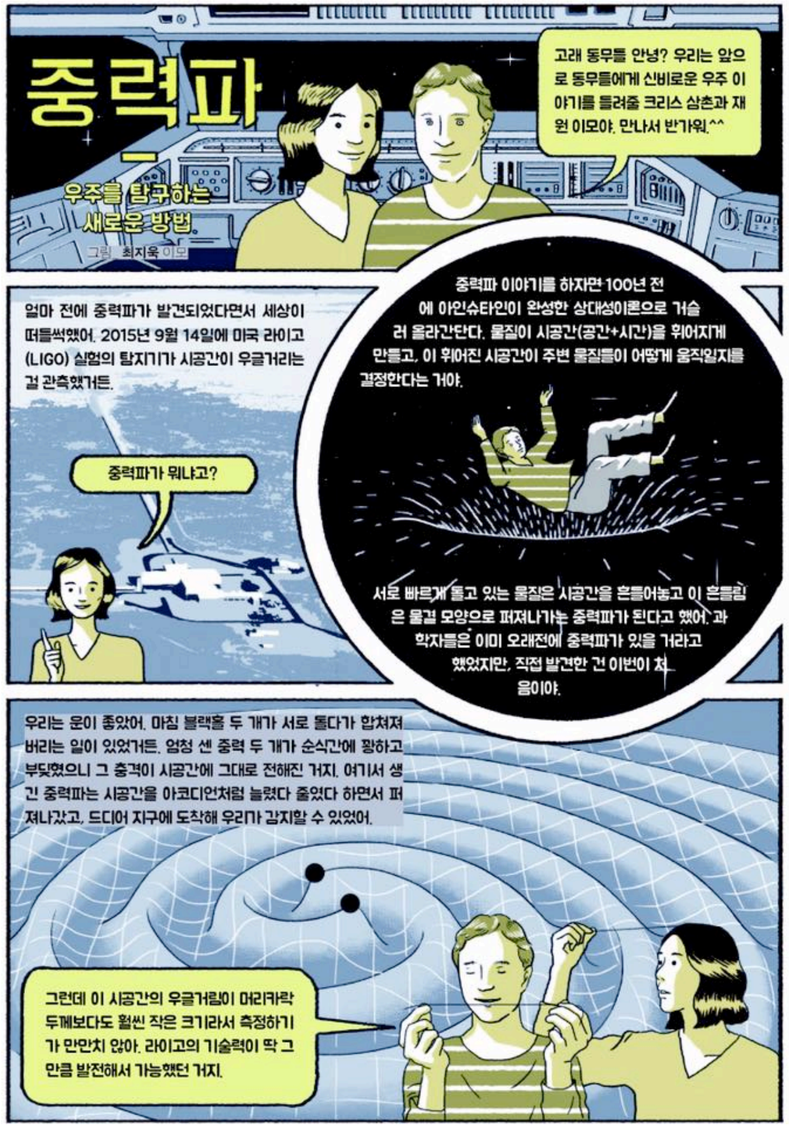
I did not think they would detected GWs in my lifetime…

So I went into cosmology

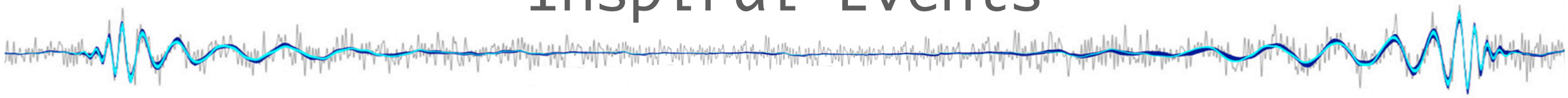
GW First Detection

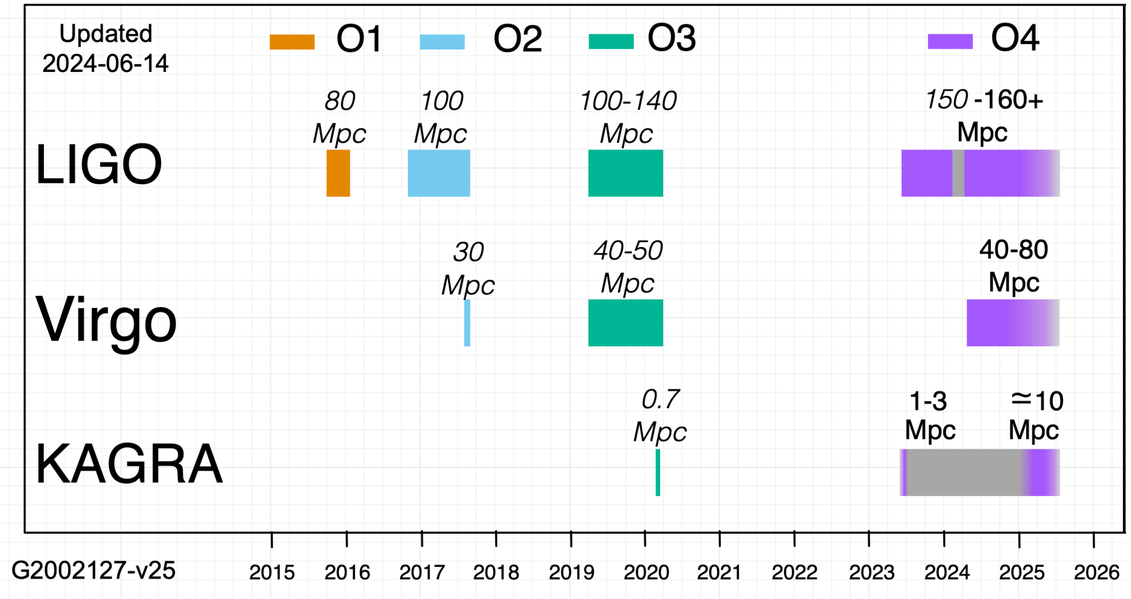
10 years later in 2016, LIGO announced the first detection of GWs

I just started writing for a kids magazine and this was our first episode with Prof Chunglee Kim (EWHA)

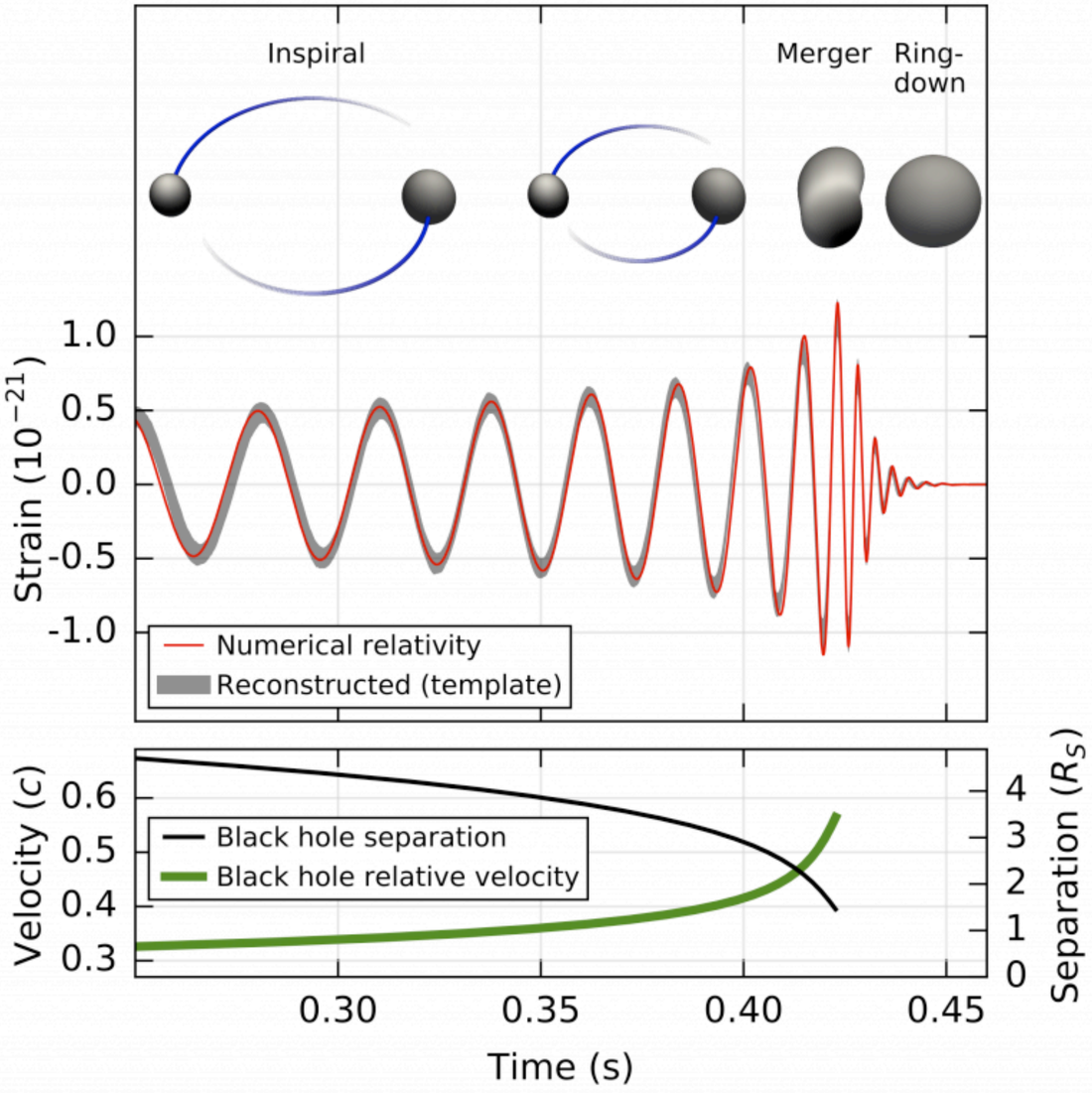


Inspiral Events





We are now in O4 of LIGO



Formation mechanisms for eccentric binaries

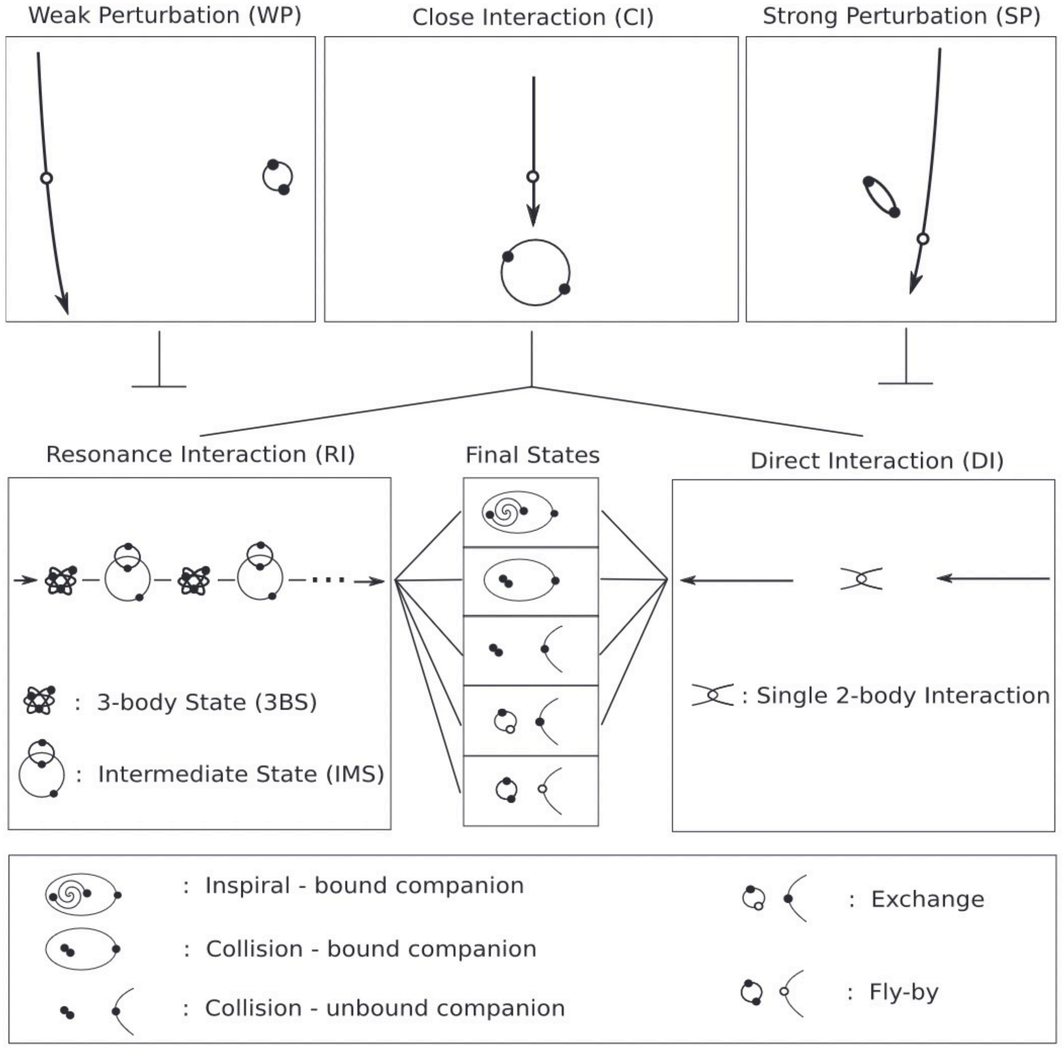


Current templated searches for GWs emanated from compact binary coalescences (CBCs)

Assume that the binaries have circularized by the time they enter the sensitivity band of the LIGO-Virgo-KAGRA (LVK) network.

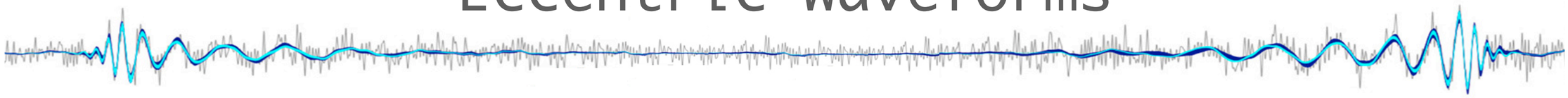
However, certain formation channels predict that in future observing runs (O4 and beyond), a fraction of detectable binaries could enter the sensitivity band with a measurable eccentricity, e.

In the near future it is expected that a significant number of inspiral events with non-negligible eccentricity will be detected by LVK

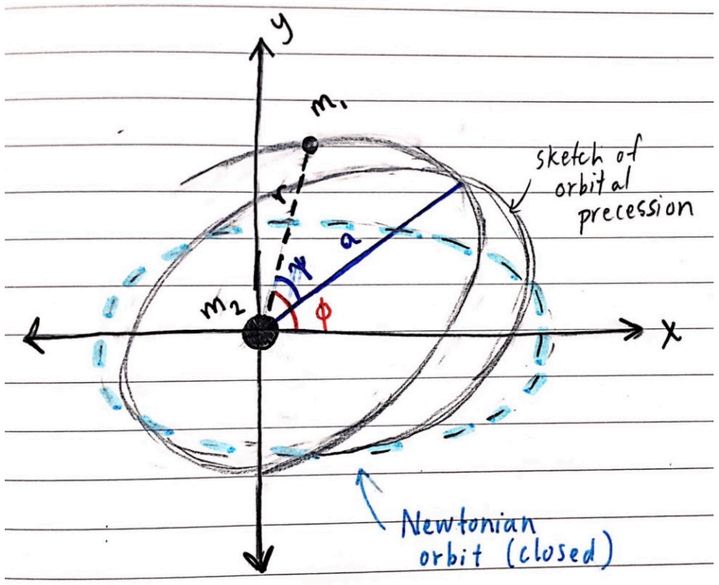


Samsing, MacLeod, & Ramirez-Ruiz ApJ 784, 2014

Eccentric waveforms

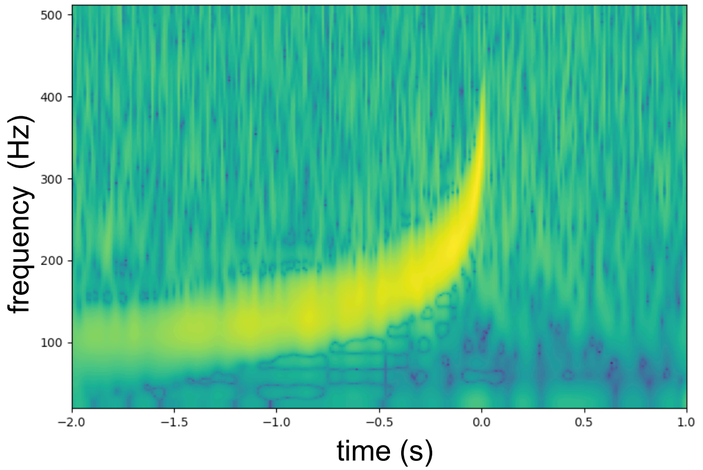


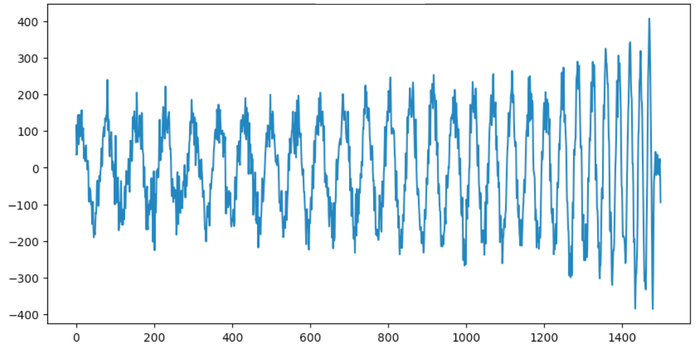
Eccentricity causes the binary's physical separation to vary



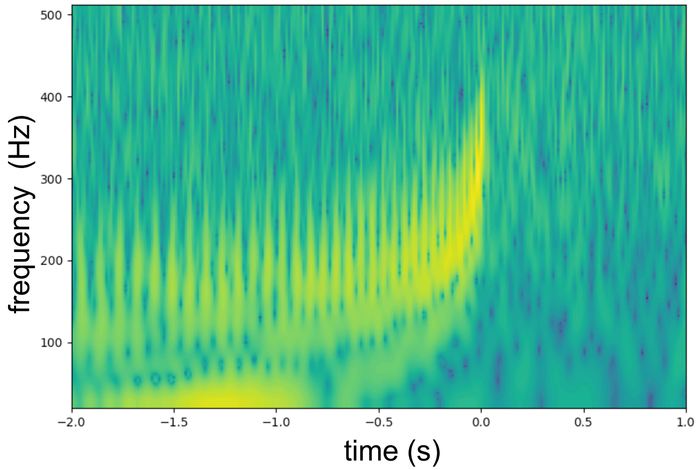
$$h(t) = \left(\frac{2G(m_1+m_2)}{c^2 d}\right)\left(\frac{2G(m_1+m_2)}{c^2 a}\right)cos(2\,\varphi(t))$$

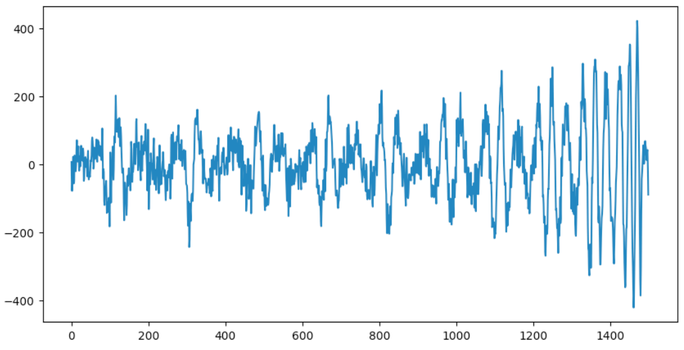
Eccentricity = 0.0



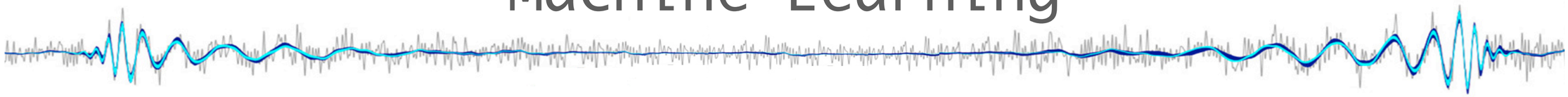


Eccentricity = 0.4





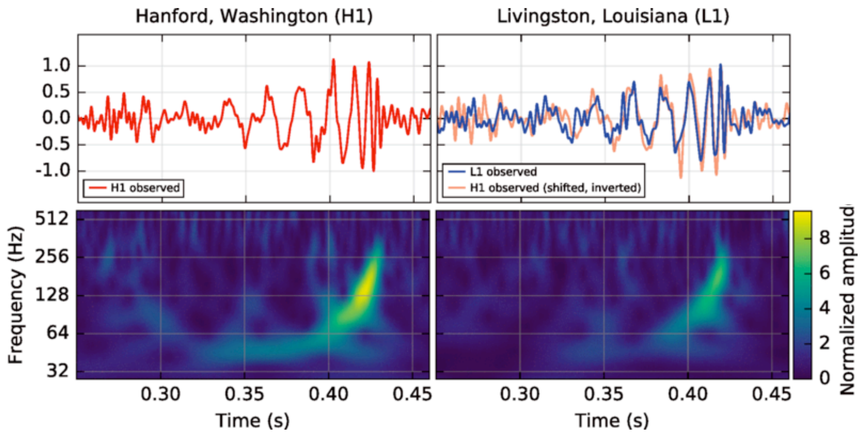
Machine Learning

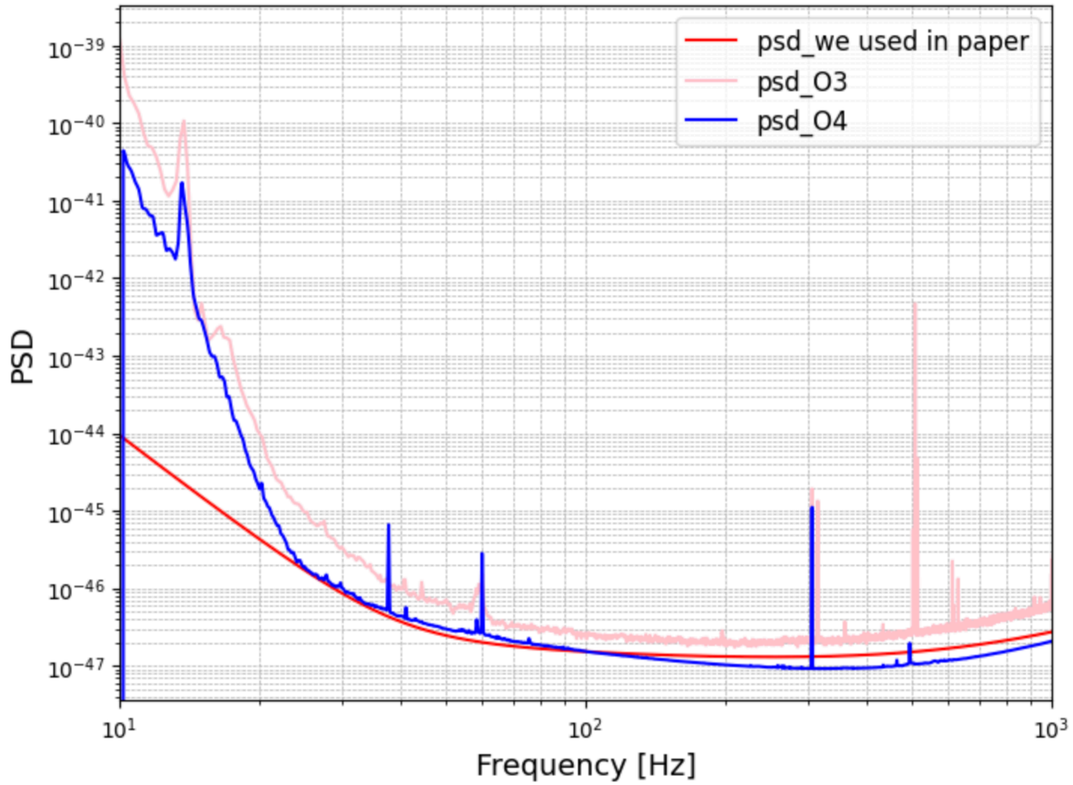


Can we use machine learning to quickly identify if an event has eccentricity or not?



CBC detection

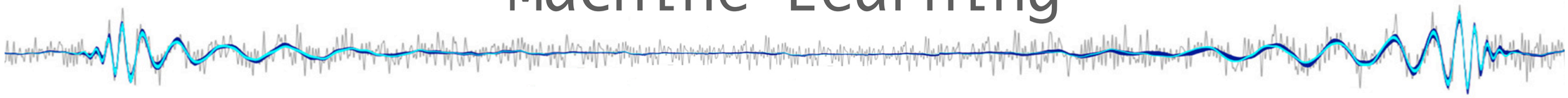




ML Magic

Detectable Eccentricity?

Machine Learning



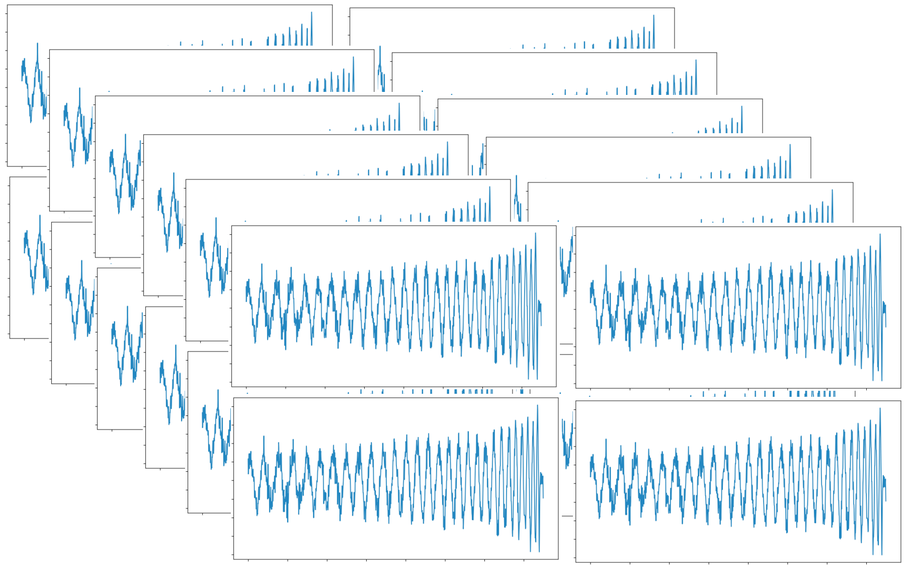
Machine Learning needs training data.

We generate 20,000 inspiral events signals with

Model: EccentricTD
Mass$_{1,2}$: $U(10, 40)$ $M_\odot$

Distance: $U(100,2000)$ Mpc

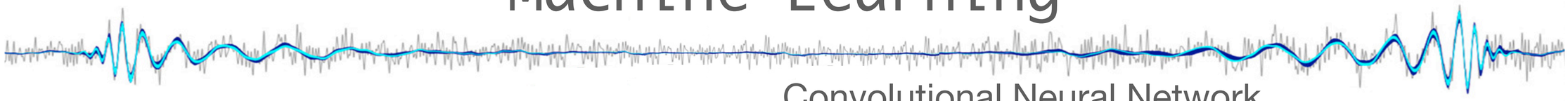
Eccentricity: $U(E-1,0.4)$



At the moment we have only generated events in one detector eg LIGO Livingstone

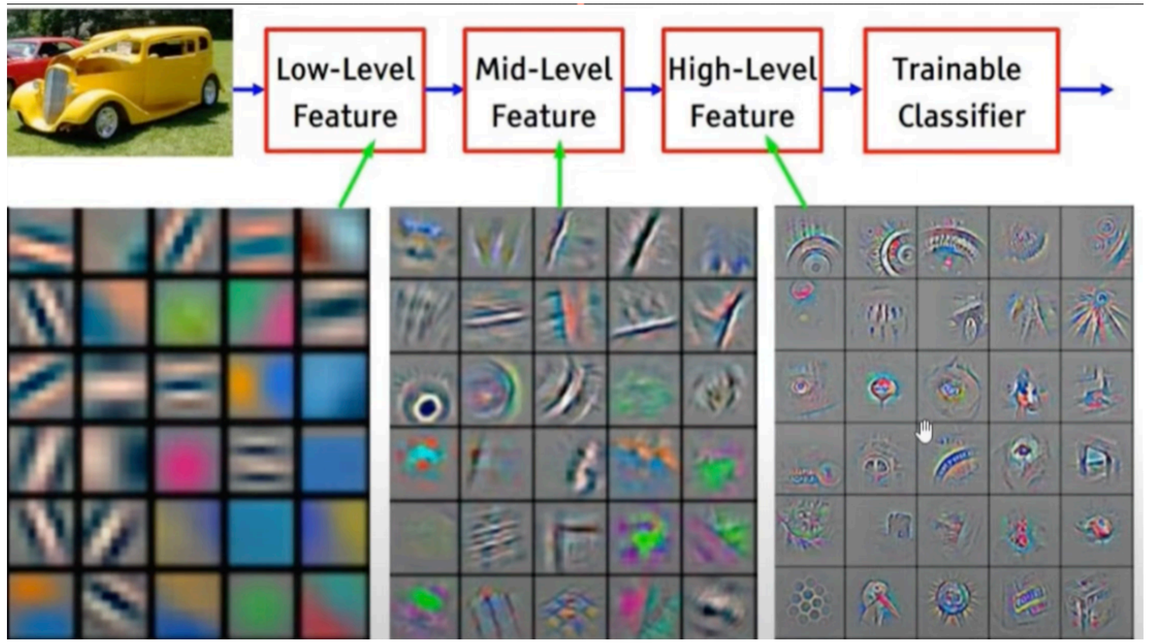
We select only events that have SNR>8

Machine Learning

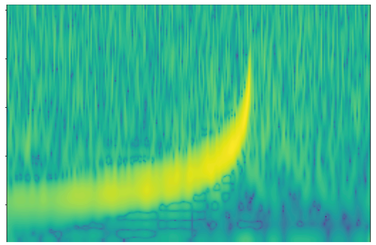


Can we use machine learning to quickly identify if an event has eccentricity or not?

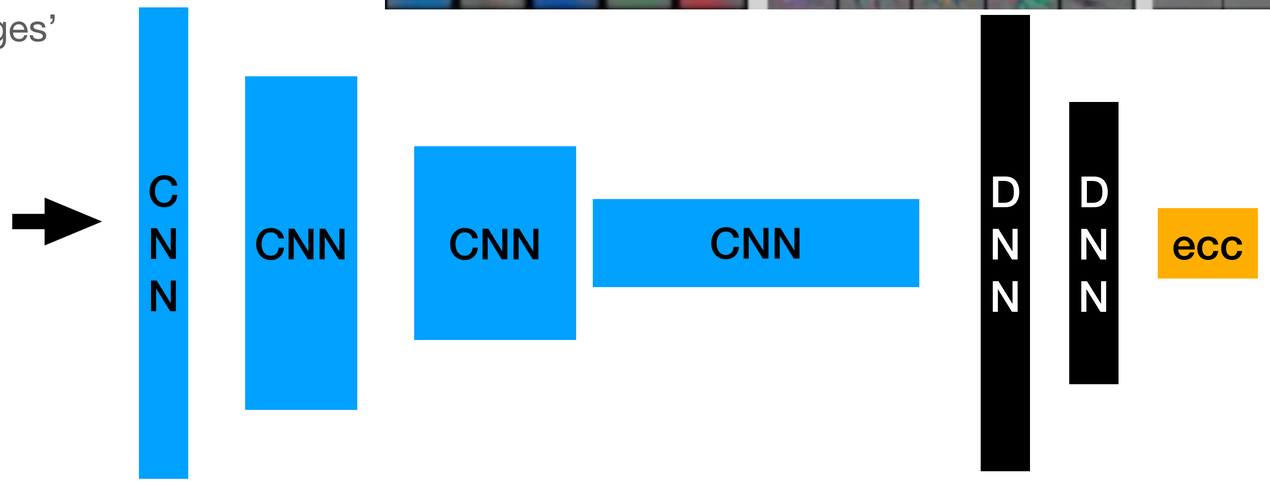
Convolutional Neural Network



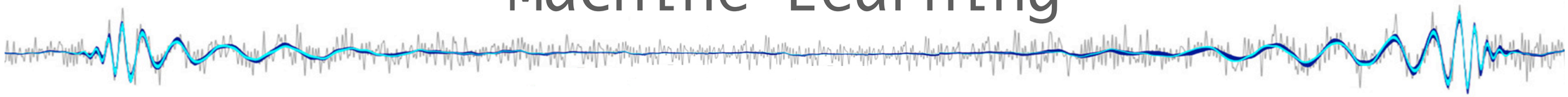
Input: 2D spectrogram ‘images’
256x256



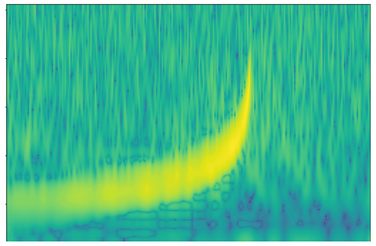
80% of training data goes in

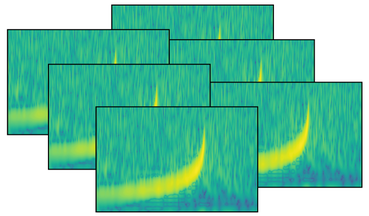


Machine Learning



Input: 2D spectrogram ‘images’
256x256





80% of data for training
20% of training for testing

Trained network

CNN

CNN

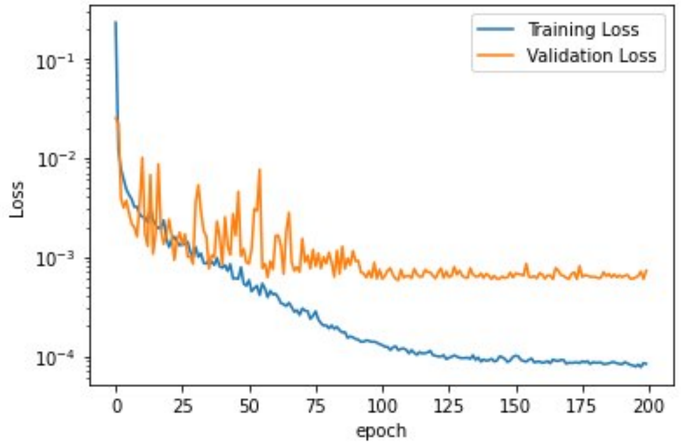
CNN

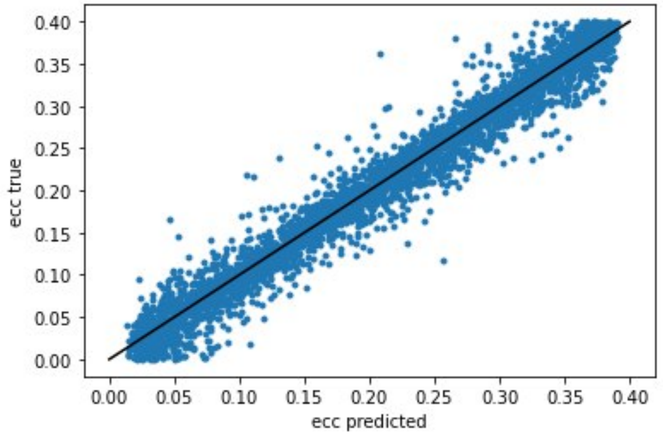
CNN

DNN

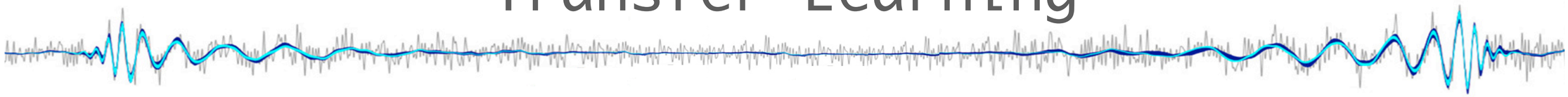
DNN

ecc





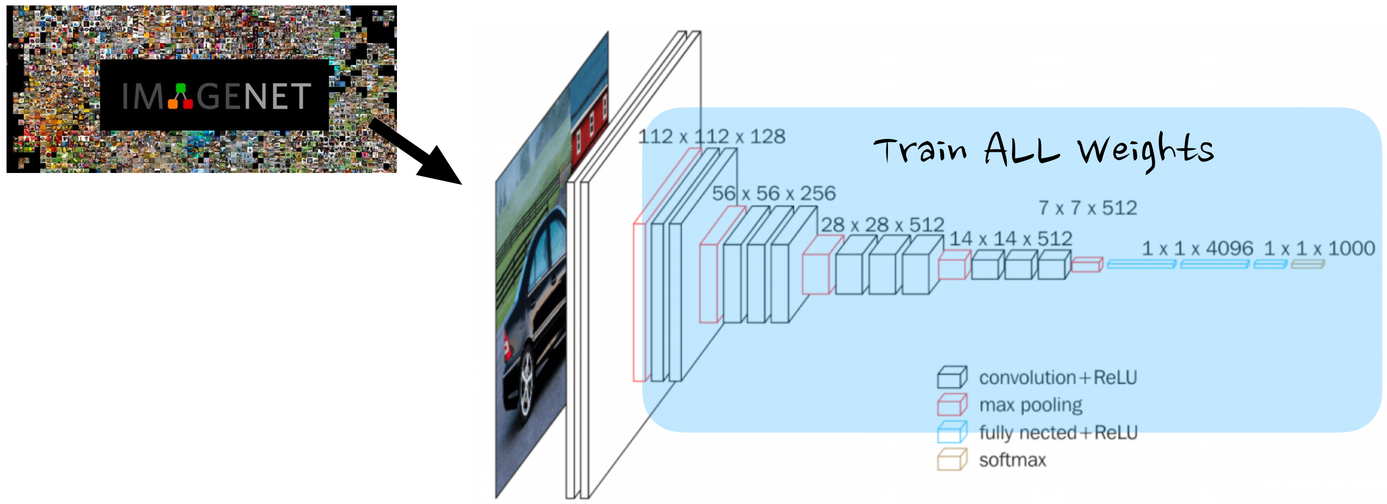
Transfer Learning



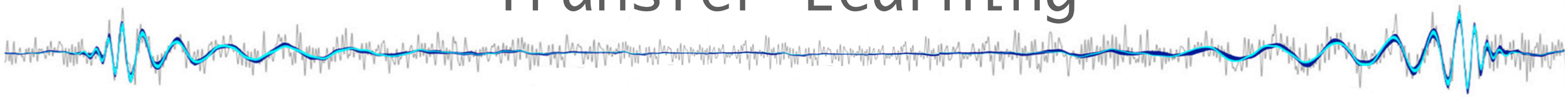
Transfer learning is the improvement of learning in a new task through the transfer of knowledge from a related task that has already been learned.

In image classification tasks many popular architectures have been trained on ImageNET - a collection of 14M images with 1,000 classes

These pre-trained networks can be downloaded and trained further on new tasks.



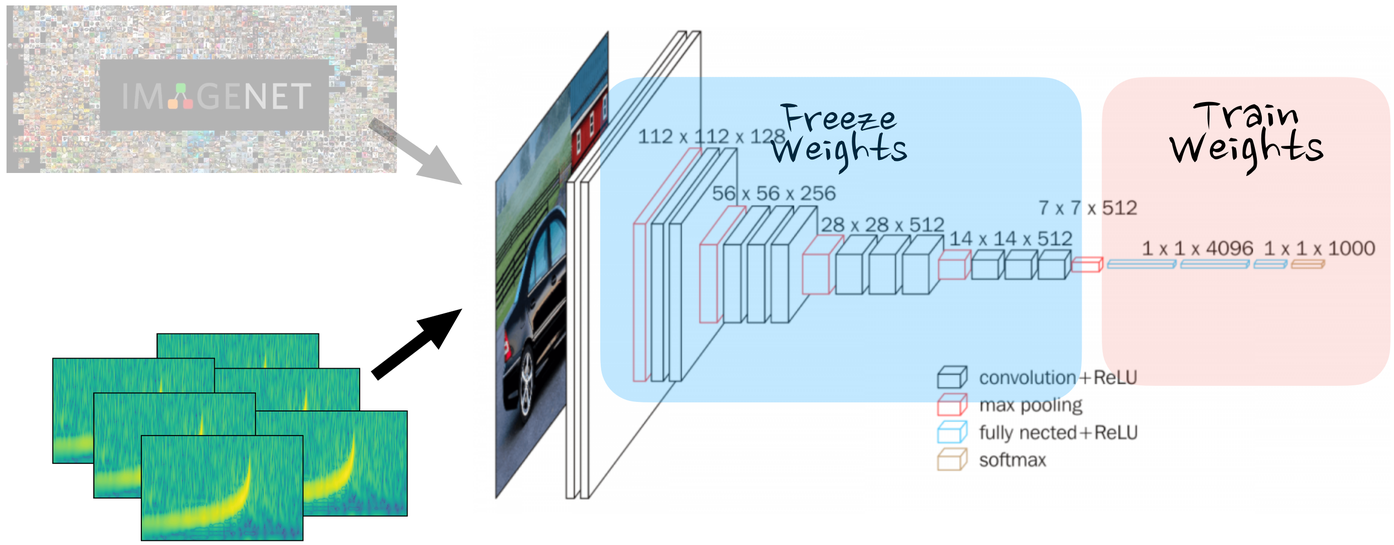
Transfer Learning

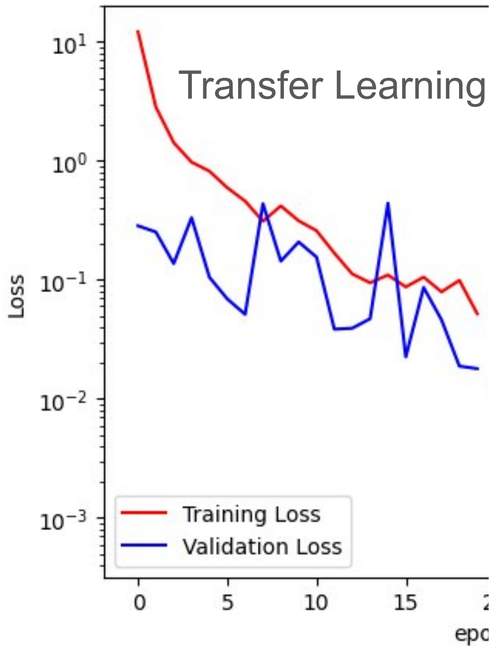


Transfer learning is the improvement of learning in a new task through the transfer of knowledge from a related task that has already been learned.

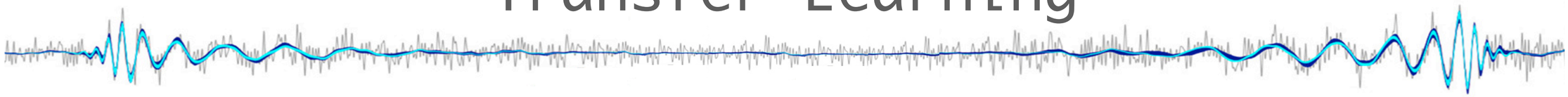
In image classification tasks many popular architectures have been trained on ImageNET - a collection of 14M images with 1,000 classes

These pre-trained networks can be downloaded and trained further on new tasks.





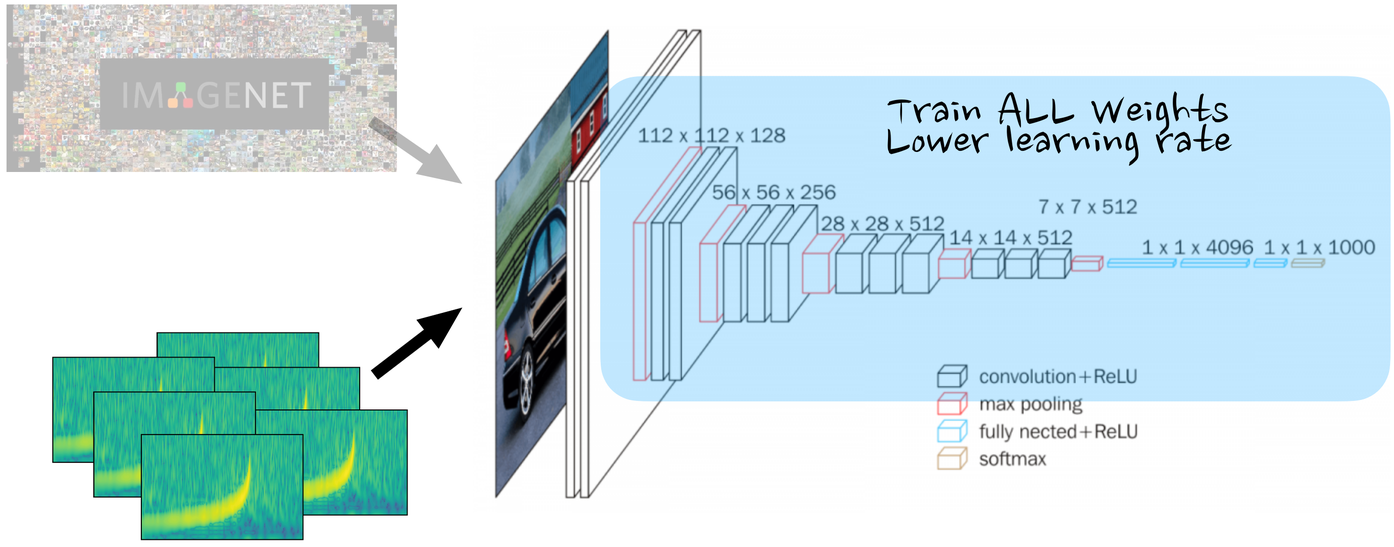
Transfer Learning

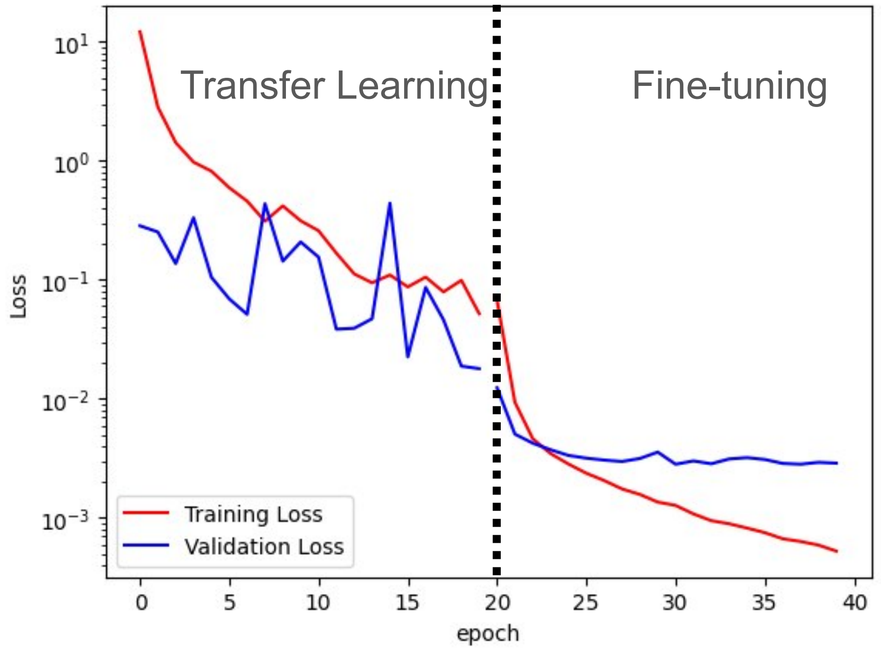


Transfer learning is the improvement of learning in a new task through the transfer of knowledge from a related task that has already been learned.

In image classification tasks many popular architectures have been trained on ImageNET - a collection of 14M images with 1,000 classes

These pre-trained networks can be downloaded and trained further on new tasks.





Model Sensitivity



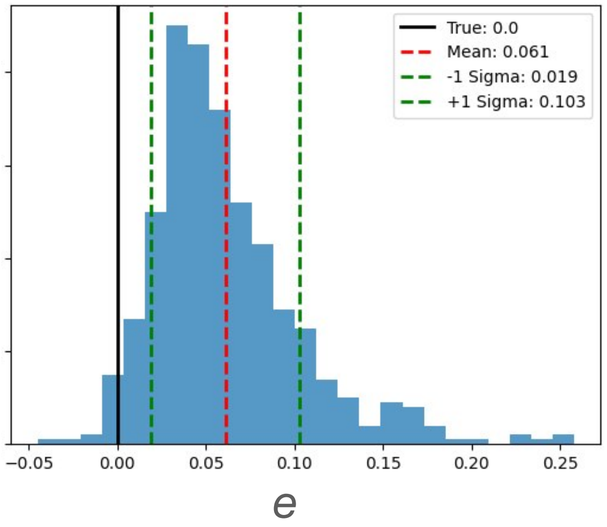
We generate 1000 events with fixed eccentricities of 0, 0.05, 0.1, 0.4

Masses, Distances are varied

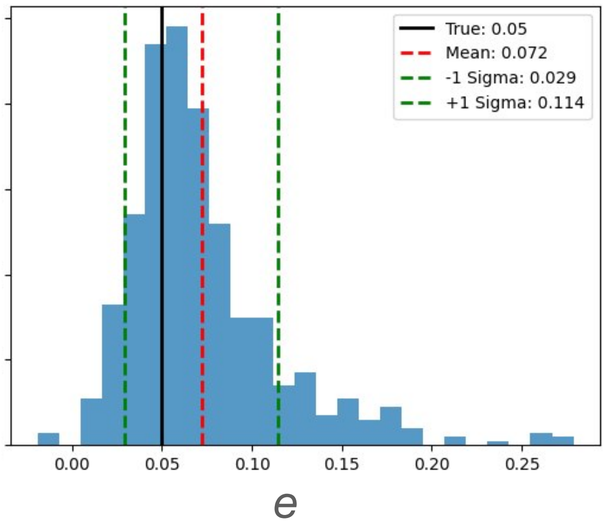
We recover well the input eccentricity for e=0.1 and 0.4

However for lower eccentricities the model struggles to clearly detect ecc

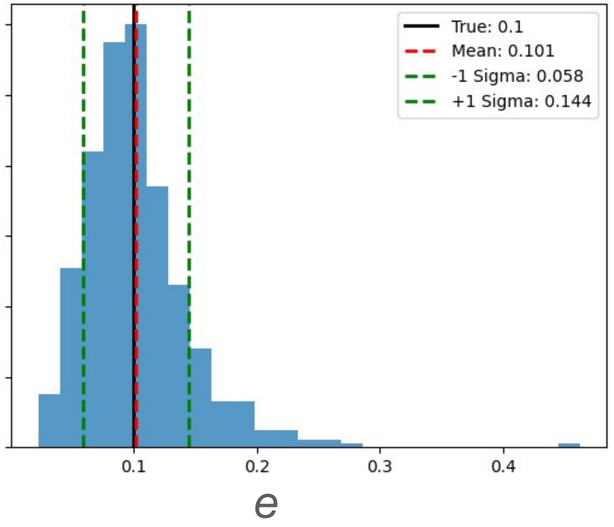
e=0.0



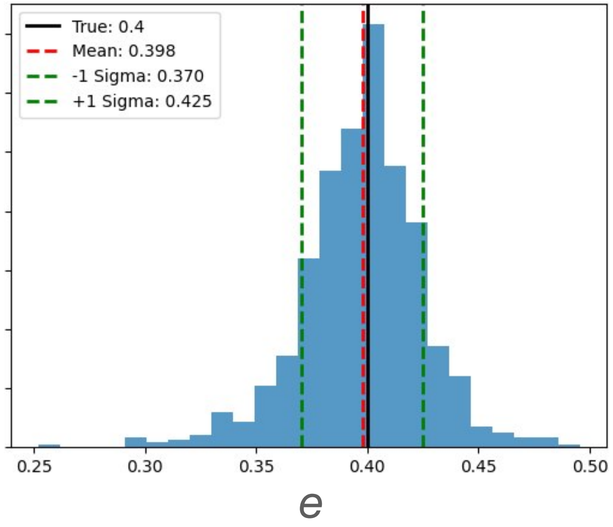
e=0.05



e=0.1



e=0.4

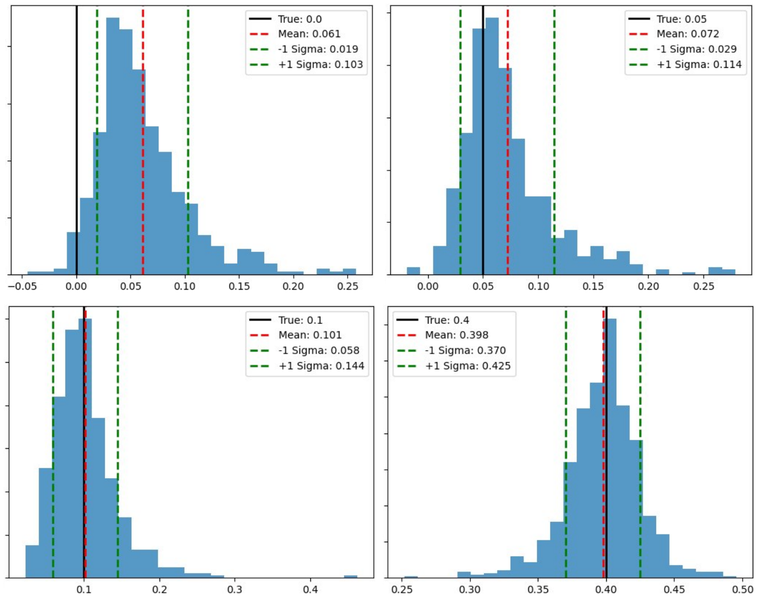


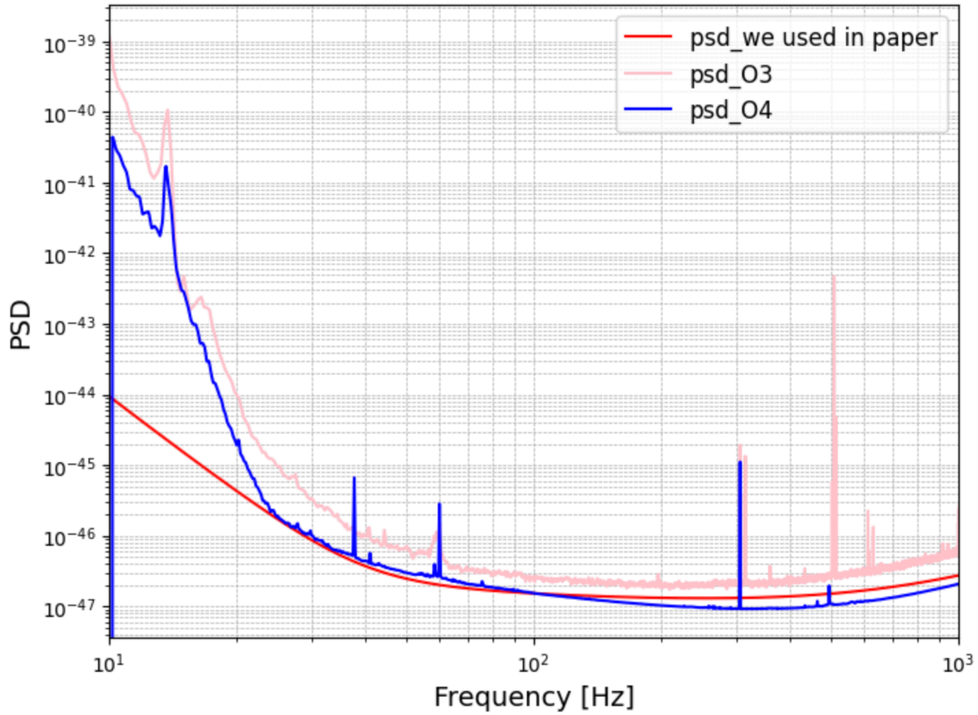
Model Sensitivity



This is ongoing work, we will soon:

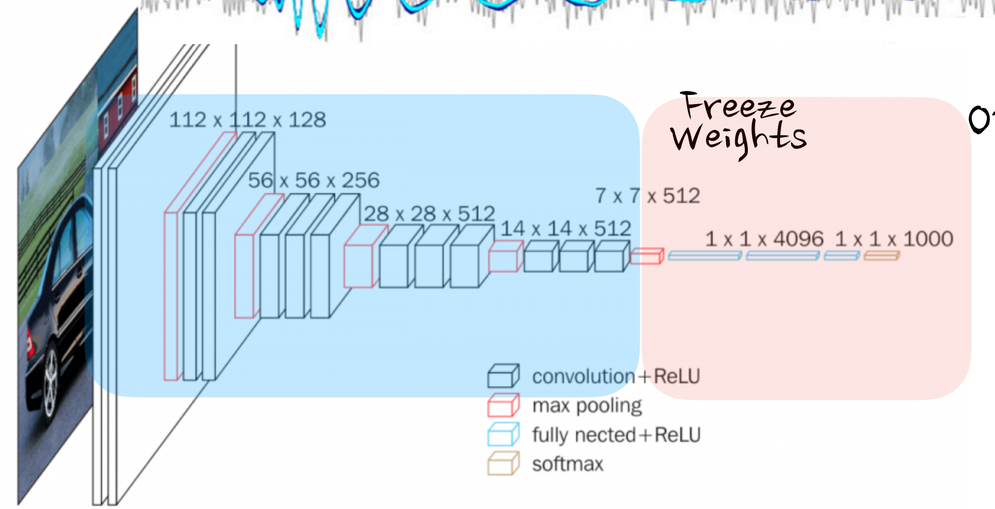
- investigate audio pertained networks which may be more inline with GW data
- add multiple detectors ie Livingston-Hanford
- simulate with more realistic noise model for O4 sensitivity
- compare our results with the standard LIGO MCMC pipelines





Ultra Diffuse Galaxy Detection

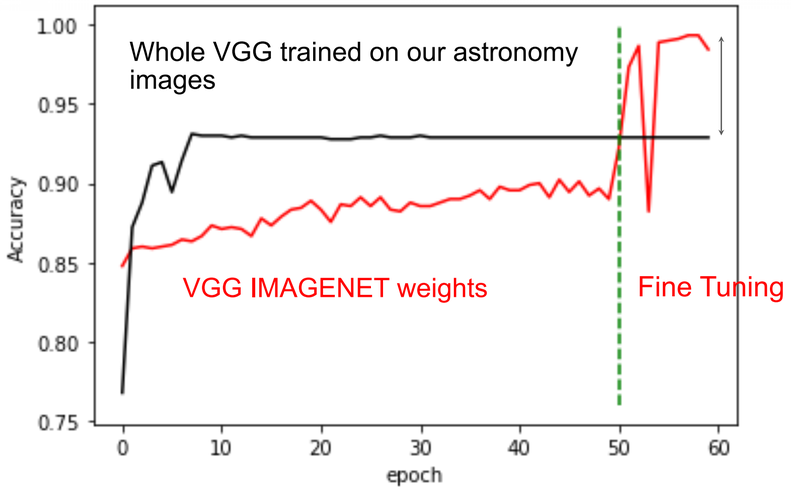


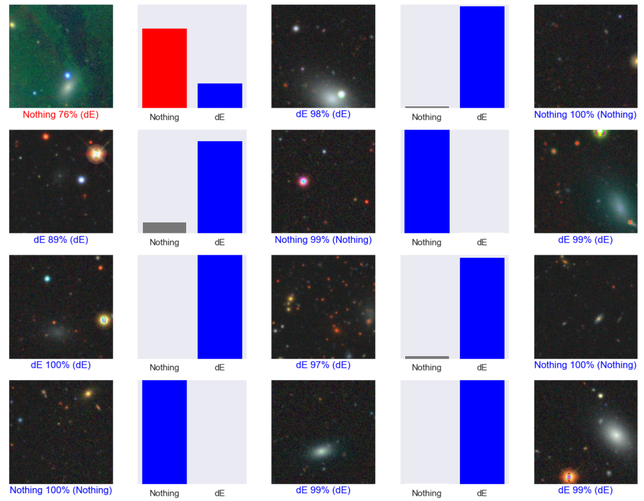


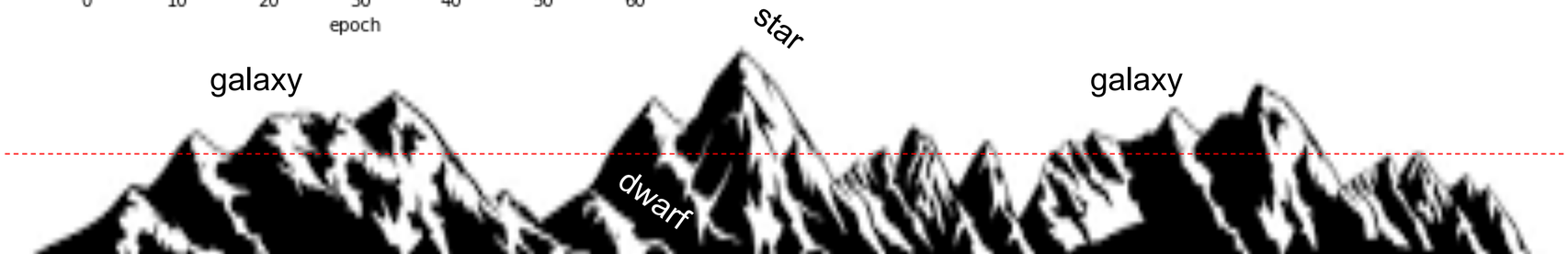
Freeze Weights

Optimize









We trained a model on 5,000 human identified dEs from DECaLS images (Paudel, et al 2023)

We now now have an extensive catalogue of dEs from the entire survey area

Lots of interesting science to do with this! Stay tuned….

(Sabiu, Paudel *in preparation*)

Ultra Diffuse Galaxy Detection

Transfer Learning is becoming a powerful tool in numerical work in astronomy….

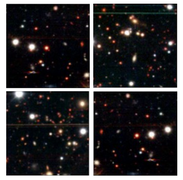
ImageNet
~14M images

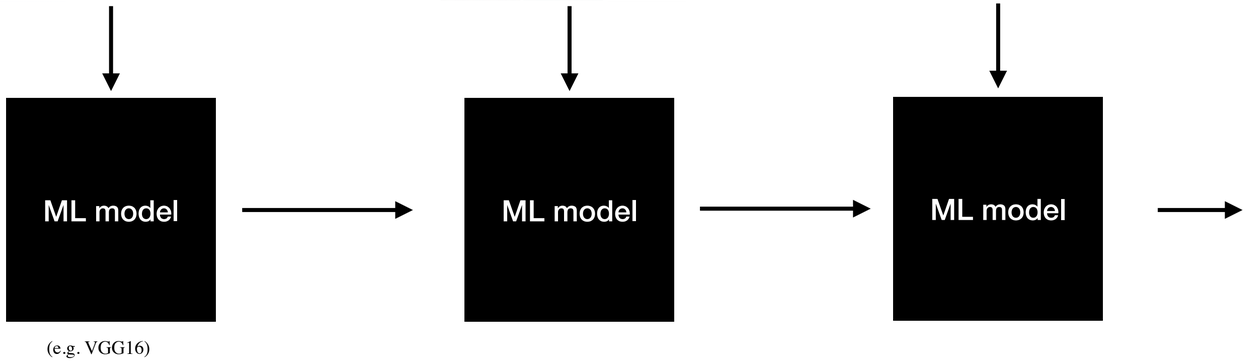


Sanjaya Paudel (Yonsei)
Dwarfs (DECaLS)
~5k images

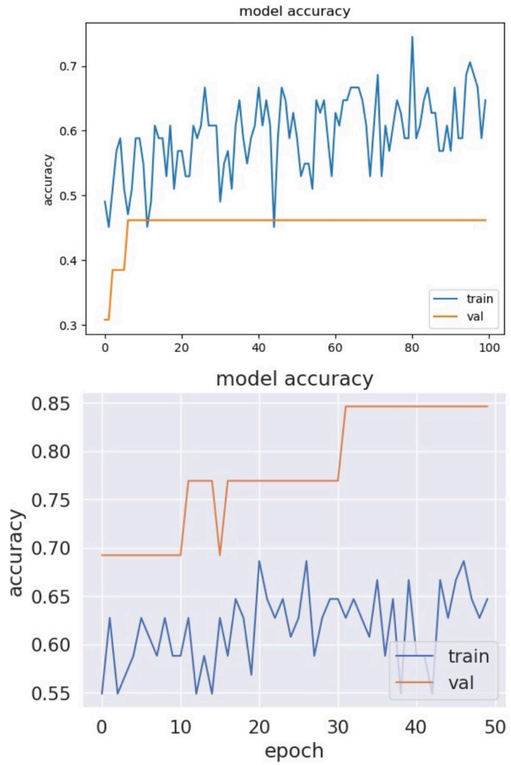


Jeehye Shin
Hong Soo Park
(KASI)
Dwarfs (KMTNet)
Only 32 images!!!!





(e.g. VGG16)



A 3-step learning process produced a surprising good result!

Caveat: very preliminary!

Shin, Park, Sabiu, et al. in preparation

This Galaxy Does Not Exist



Latent Diffusion Models (LDMs) have become very popular inn the last few years
They provide a way to generate new images from an existing training set.
LDMs are robust against mode-collapse and training instabilities compared to GAN.

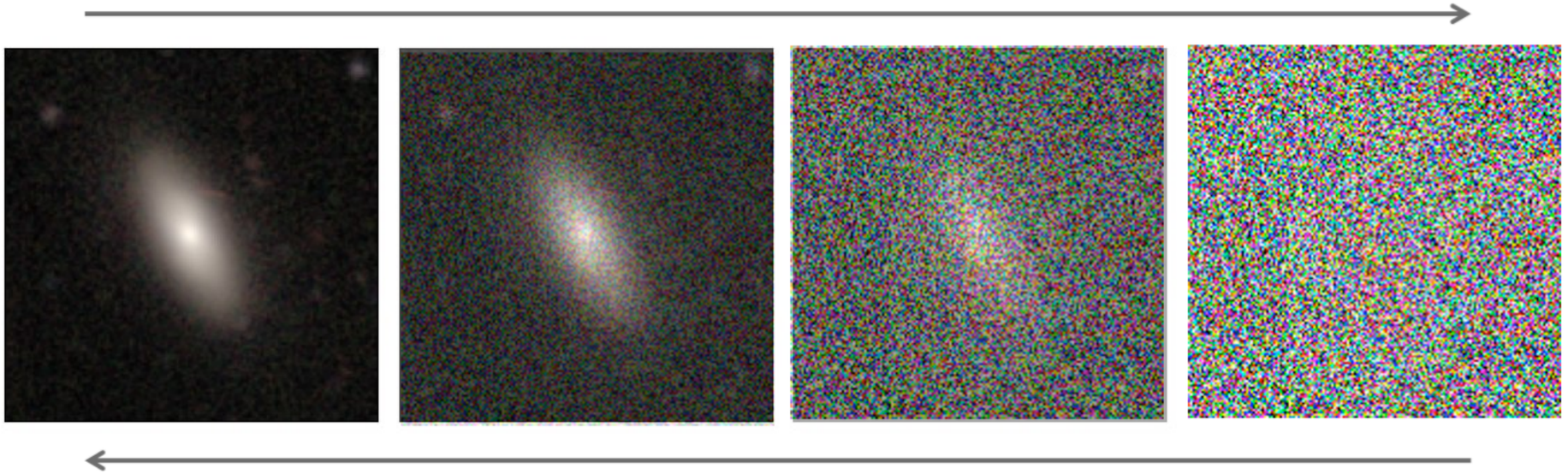


Probabilistic models that can generate high-quality images by starting with random noise and gradually transforming them into realistic images through a diffusion process.

This Galaxy Does Not Exist



Latent Diffusion Models (LDMs) have become very popular inn the last few years
They provide a way to generate new images from an existing training set.
LDMs are robust against mode-collapse and training instabilities compared to GAN.



Probabilistic models that can generate high-quality images by starting with random noise and gradually transforming them into realistic images through a diffusion process.

This Galaxy Does Not Exist



Which are real A or B?

A



B



Sungjin Yang, Watson, Sabiu *in preparation*

This Galaxy Does Not Exist

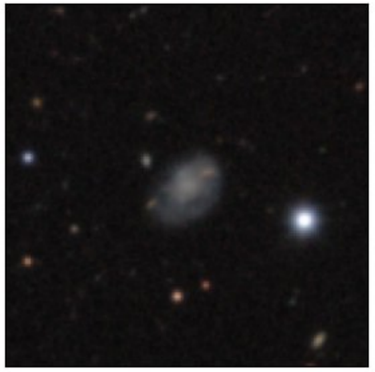
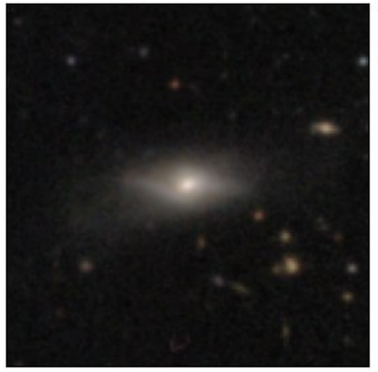


Which are real A or B?

A

Real



B

Fake







Sungjin Yang, Watson, Sabiu *in preparation*

Conclusions



Transfer Learning is a power method that can be applied to many classification or regression problems

In future LIGO-Virgo-Kagra observing runs we will see many events with detectable eccentricity so we should develop methods to rapidly detect/characterise source eccentricity

Pretrained Image networks working well, we are now implementing audio pertained networks to see if there is any improvement

We are now adding multiple detectors (ie Livingston-Hanford), and making more realistic noise data with O4 sensitivity